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14. ABSTRACT
Recycling unmeasured photons in a system utilizing weak measurements can substantially improve the signal-to-noise ratio. We have performed a complete theoretical analysis of the tradeoffs, and demonstrated in a double-pass system that we could achieve an improvement by a factor of 1.36 over a system with no recycling. We also begin preliminary investigation into combining quantum states of light.

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Report Title

Final Report: STIR: Advanced Quantum Sensing

ABSTRACT

Recycling unmeasured photons in a system utilizing weak measurements can substantially improve the signal-to-noise ratio. We have performed a complete theoretical analysis of the tradeoffs, and demonstrated in a double-pass system that we could achieve an improvement by a factor of 1.36 over a system with no recycling. We also begin preliminary investigation into combining quantum states of light.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
07/14/2014	2.00	Justin Dressel, Kevin Lyons, Andrew N. Jordan, Trent M. Graham, Paul G. Kwiat. Strengthening weak-value amplification with recycled photons, Physical Review A, (08 2013): 23821. doi: 10.1103/PhysRevA.88.023821
TOTAL:		**1**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper
TOTAL:	

Number of Papers published in non peer-reviewed journals:

(c) Presentations

"Increasing the Signal-to-Noise Ratio in Weak-Value Measurements"
C. Byard, T. Graham, A. Danan, A. Jordan, and P. Kwiat
Quantum Information and Measurement 2013 - Rochester (June 17-20, 2013)

"Weak values: the progression from quantum foundations to tool", Andrew Jordan
Invited colloquium - University of Arizona, Tucson, AZ (September 2012).
Invited talk - University of Geneva, Geneva, Switzerland (August 2012).
Invited talk - Yakir Aharonov 80th birthday conference, Orange, CA (August 2012).

Number of Presentations: 4.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper
07/17/2014 3.00	Courtney Byard, Trent Graham, Arial Danan, Lev Vaidman, Andrew Jordan, Paul Kwiat. Increase of Signal-to-Noise Ratio in Weak Value Measurements, Aharonov 80: 80th Birthday Celebration for Yakir Aharanov. 16-AUG-12, . : ,

TOTAL: 1

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Courtney Byard: 2013 National Science Foundation Graduate Research Fellowship
Awarded: March 2013
Funding began: September 2013

Andrew Jordan: invited to be a member (affiliated scholar) of Institute of Quantum Studies at Chapman University (2013)

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Courtney Byard	0.67	
Trent Graham	1.00	
Justin Dressel	0.00	
FTE Equivalent:	**1.67**	
Total Number:	**3**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Paul Kwiat	0.00	
Andrew Jordan	0.06	
FTE Equivalent:	**0.06**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 0.00

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME
Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

1 a. University of Rochester

1 b. 518 Hylan Bldg.

Rochester NY 146270140

Sub Contractor Numbers (c): 2012-05119-01

Patent Clause Number (d-1): 215.36

Patent Date (d-2): 8/31/05 12:00AM

Work Description (e): Prof. Andrew Jordan and students are providing the detailed theoretical support for this pr

Sub Contract Award Date (f-1): 8/14/12 12:00AM

Sub Contract Est Completion Date(f-2): 4/30/13 12:00AM

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Inventions (DD882)

Scientific Progress

Pleas see Attachment.

Technology Transfer

STIR: "Advanced Quantum Sensing" Final Report

1.1 Background and Introduction

The results of measurements on a quantum mechanical system are among the most basic predict-tions of quantum theory. However, in the last two decades there have been several measurement phenomena introduced that capitalize on the usual simple strong "projective measurements" of standard quantum mechanics; these approaches have led to unprecedented advances in precision measurements or metrology. In many cases the observable one is trying to measure leads to an effect that is much smaller than the intrinsic quantum mechanical uncertainty in that degree of freedom. For example, one might be attempting to detect the shift of a quantum mechanical wavepacket which is much less than the width of that wavepacket. In such cases, it is now known that by making an appropriate pre- and post-selection one can achieve large amplification of the desired measurable observable [1]. Specifically, the weak value A_W of the measurement of observable *A* is given by

$$A_W = \frac{\langle \varphi_2 | A | \varphi_1 \rangle}{\langle \varphi_2 | \varphi_1 \rangle},$$

which can be much larger than the usual expectation value, if the pre- and post-selected states $|\varphi_1\rangle$ and $|\varphi_2\rangle$ are nearly orthogonal. Because one detects only a small fraction of the overall ensemble when making the post-selection, weak measurements do not, in fact, allow one to beat the so-called Standard Quantum Limit (SQL), where measurement uncertainties scale as $1/\sqrt{N}$, (N is the number of photons) instead of the much more sensitive Heisenberg scaling of $1/N$. Nevertheless, the weak measurement amplification does also reduce technical noise by the same factor [1]. For example, in our recent demonstration of the optical Hall effect of light [2], we were able to detect sub-nanometer displacements of a millimeter-diameter laser beam, despite the fact that the entire experiment was performed on a non-floating optical table.

In addition to the intrinsic interest of being able to monitor quantum wave functions without completely collapsing them [3], the reduction of technical noise by weak amplification is potentially of tremendous practical value in real measurement systems. Previous experiments are limited by the post-selection required by this technique. During this post-selection much of the light is discarded, leaving only a small portion of the initial intensity to contribute to the measurements. For this project we proposed a method for *recycling* the light typically lost from post-selection, so most of the initial intensity is eventually detected. Because, for a shot-noise limited interferometer, the signal-to-noise ratio (SNR) is proportional to the square root of the number of photons incident on the detector, collecting a larger portion of the incident light can increase the SNR substantially.

Consider the interferometric weak-value experiment by Howell et al., where light was sent into a Mach-Zehnder interferometer, one of whose mirrors could be tilted slightly [4]. The goal was to detect the slight angular deviation imprinted on the beam, though this tilt was much smaller than the intrinsic angular divergence of the beam, i.e., a weak measurement. The post-selection was performed by measuring in the "dark" port of the interferometer. The interference of the slightly deflected beam with the undeflected beam from the other arm of the interferometer leads in this dark port to a displacement of the centroid of the beam that is amplified by $1/\sqrt{P}$, where P is the post-selection probability, i.e., the probability that a photon exits by the dark port. The centroid is then measured using a position-sensitive detector such as a quadrant-cell photodiode.

Using these methods, Howell et al. were able to achieve angular resolutions as small as 400 femtoradians. Although this was a tremendous result, one obvious drawback is that most of the photons are not used for the measurement. Instead, the majority of the incident light still exits by the non-dark port of the interferometer, in essentially the same spatial mode as was input to the interferometer. This is the essential point that underlies the possibility to perform *cyclic* weak measurements: we can redirect these unused photons back through the interferometer for repeated attempts at weak measurement. In this way, *every* photon is in principle eventually post-selected.

1.2 Experimental Results

To demonstrate the principle underlying our cyclic weak measurement concept, we constructed a double-pass Sagnac interferometer* which allowed light usually discarded in post-selection to pass through the interferometer a second time (see Fig. 1). Because only a small fraction of the light escapes via the dark port in the first pass (the rest being directed back toward the source), essentially the same amount of light exits on the second. Thus the total number of photons incident on the detector is nearly doubled with this configuration. We expect the signal, which is proportional to the number of incident photons, to double as well. In the shot-noise-limit the noise scales as the square root of the number of photons, and hence we expect the noise to only increase by a factor of ~1.4 (=√2) over the single-pass configuration. Thus, the SNR should also be increased by a factor of 1.4.

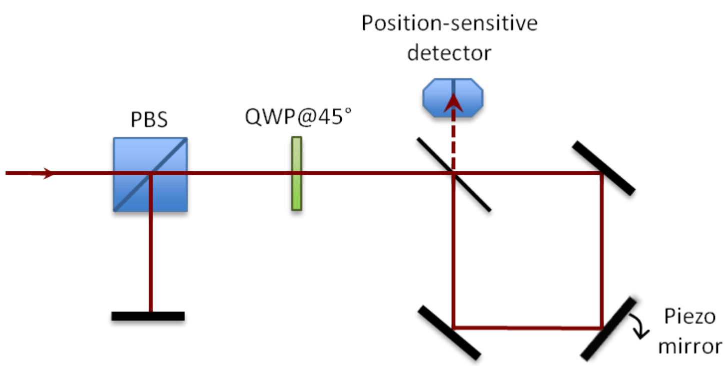


Fig. 1 Implemented double-pass scheme. A polarizing beam-splitter (PBS) passes horizontally (H) polarized light incident from a fiber-coupled laser. Light is then switched to left-circularly polarized by a quarter wave plate (QWP). After passing through the Sagnac, the QWP switches the polarization to vertical (V). Light is now reflected at the PBS to another mirror, which sends the beam back through the system for a second pass.

A 633-nm laser was coupled to a single-mode fiber and the output then collimated to a radius of 1 mm. A QWP and half-wave plate were used to adjust the intensity. As shown in Fig. 1, the beam was then passed through a polarizing beamsplitter (PBS) and QWP, switching the polarization to left circularly polarized. A 50-50 beamsplitter split the light into clockwise and counter-clockwise arms of the Sagnac interferometer. Mirror 1 was tipped slightly out of the plane of the beam path, causing an adjustable path length difference (since the clockwise path experiences the tilt first) which was used to control the relative phase. To measure the weak value, Mirror 2 was tilted in the plane of the interferometer with a piezoelectric crystal (Thorlabs #KC1-PZ) with a 500-Hz sinusoidal voltage for a range of amplitudes. The resulting shift was measured with a quadrant cell detector (New Focus #2921) and the output signal filtered with a lock-in amplifier (SR830). Position shifts were determined by normalizing the voltage difference between the left and right photodiodes by the total voltage. Results are shown in Fig. 2. Light

* The Sagnac affords *much* better phase stability than, e.g., a Mach-Zehnder interferometer; a tilt of the one of the mirrors (about an axis normal to the plane of the Sagnac) deflects the clockwise and counter-clockwise paths in opposite directions, while any other disturbances affect both paths equally.

that exited the bright port, now right circularly polarized, again passed through the QWP and was switched to vertical polarization. At the PBS, the light was then reflected to a mirror to be sent through the system a second time. The interferometer was square with sides about 4 cm, with a path length of approximately 26 cm from mirror 2 to the detector. The maximum power achieved at the detector output port of the interferometer was 2 mW; the minimum output power was about 6 μW, corresponding to a visibility of 99.4%. We tested the system at two different phases so that when shifted to the chosen post-selection probability, 36 μW or 67 μW exited to the quadrant cell detector for the single-pass data (corresponding to a relative phase difference of 15 or 21 degrees), while approximately 72 μW or 134μW exited for the double-pass data.

As expected, our measurements show that the signal from the position-sensitive detector (normalized difference between the voltages of the left and right photodiodes) of the double-pass system is approximately equal (see Fig. 2), but the uncertainty in beam position is reduced. Our results indicate that the SNR is consistently larger for the double-cycle case over the single cycle, as we observed an average SNR increase by a factor of 1.36 ± 0.41. (Because the small deflection and uncertainty in the measurements makes the error bars on the SNR ratio quite large, we weighted 33 measurements by the reciprocal of the standard deviation.) Though this seems to be consistent with the anticipated behavior of a shot-noise limited system, we do not observe that in this case our measurement was really shot-noise limited. We expect electronic noise in the detector to limit the resolution to about 20 picoradians, while the shot noise limit would be about 2 picoradians. The actual resolution of our setup in this configuration was approximately 50 picoradians. For a system limited by technical noise that is independent of the number of cycles (e.g., electrical noise from the detector itself), the doubling of the signal is not accompanied by an increase in noise, and should result in a doubling of the SNR. Hence, our experiment suffered from some noise which is not yet fully understood. In the current project we moved to a quantum-level experiment (using photon counters), where the substantially larger relative shot-noise now dominates.

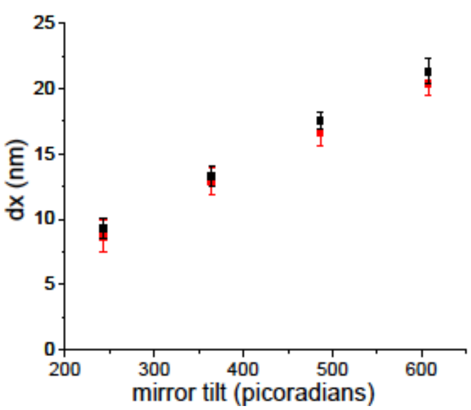


Figure 2: Normalized voltage difference between left and right photodiodes for double- (black) and single-pass (red) systems for a representative experiment. Both show the same displacement, but the uncertainty in the double-pass data is smaller by a factor of 1.36.

With an n-cycle scheme, the benefits of recycling could be maximized. If the light is recycled until all photons are either detected or lost to absorption, the maximum sensitivity achievable with weak measurements should be significantly increased even over the 2-cycle scheme described above. An n-cycle experiment can be realized in a similar fashion to the double-pass scheme, except a Pockels cell (a fast birefringent switch) replaces the QWP and a pulsed laser is used; we are currently implementing this scheme. Estimating minimum achievable losses from post-selection and absorption at about 0.5% each cycle, we can place an upper bound of about 100 recycled rounds per pulse. Thus, the SNR could be increased by an order of magnitude, pushing the measurable deflection limit substantially lower.

1.3 Theory Results

We have found [5] that our recycling strategy does indeed lead to an improvement in the signal-to-noise ratio of the desired parameter, effectively given by the power increase of the split-detection signal on the position-sensitive detector. Moreover, since even a single-pass weak-value amplification already achieves the sensitivity of standard measurement techniques (such as homodyne detection) but with lower technical noise [6], the improvements from recycling should *exceed* the sensitivity of the standard techniques, even when they are shot-noise limited.

The signal-to-noise ratio (SNR) at the detector is defined as the ratio of the collected signal to the square root of the variance of that collected signal. A SNR of unity will roughly correspond to the smallest resolvable signal. Hence, finding ways to increase the SNR ratio without changing the source of the signal will increase the sensitivity of the measurement. The total accumulated signal scales linearly with the average collected energy, which is the average power at the detector P_d times the collection duration t. For a coherent source, the variance of the split-detected signal is the total collected intensity. Hence, the SNR will scale as $\sqrt{P_d t}$; obviously, the SNR can be increased either by waiting for a longer duration or by increasing the effective power at the dark-port detector. The recycling scheme will increase the average power so that a measurement of the same duration and source power will have higher sensitivity. So long as the beam profile remains constant (not necessarily true; see below) and losses are not large, the gain in SNR will be proportional to the square-root of the recycling number. Theoretical calculations indicate this is indeed the case for small cycle numbers, as shown in Fig. 3.

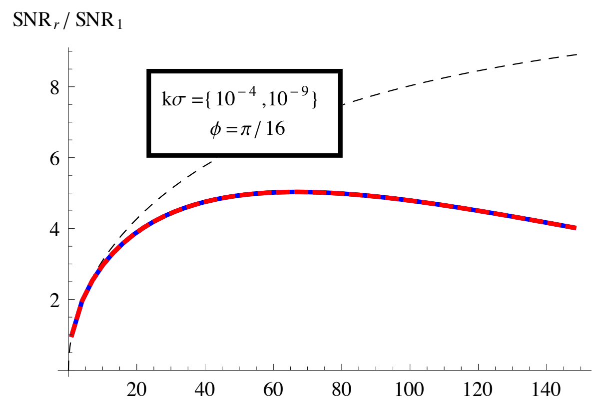


Fig. 3 The enhanced SNR scales as the square root of the cycle number (r), so long as the cycle number is small. Dashed line indicates this optimal scaling; the full theoretical prediction gives sub-optimal behavior, originating from walk-off behavior (see below). Plot is for fixed phase shift φ between interferometer paths. σ is the beam width, and k is proportional to the momentum kick from the mirror.

However, as seen in Fig. 3, for larger values of r, the SNR begins to *decrease*; the reason can be seen in Fig. 4—starting from a Gaussian beam profile, subsequent traversals have similar intensities, but progressively walk toward the center with increasing r, as more and more photons are taken away from the dark port.

To eliminate the walk-off effects and gradual deterioration of the remaining beam profile shown here, we considered two strategies:

a. Use an image rotation element (e.g., a dove prism) to flip the spatial mode of the light coming out of the interferometer bright port on each cycle (i.e., effect the operation $\xi(x) \rightarrow \xi(-x)$). As a consequence of this mode reflection in each cycle, the ‘etching away’ of the spatial mode from the weak measurement now effectively occurs on alternating sides of the beam, so that there is net walkoff of the tilted beam back to its central un-shifted Gaussian. In other words, such mode reflection should act to stabilize the recycled-light spatial mode, so

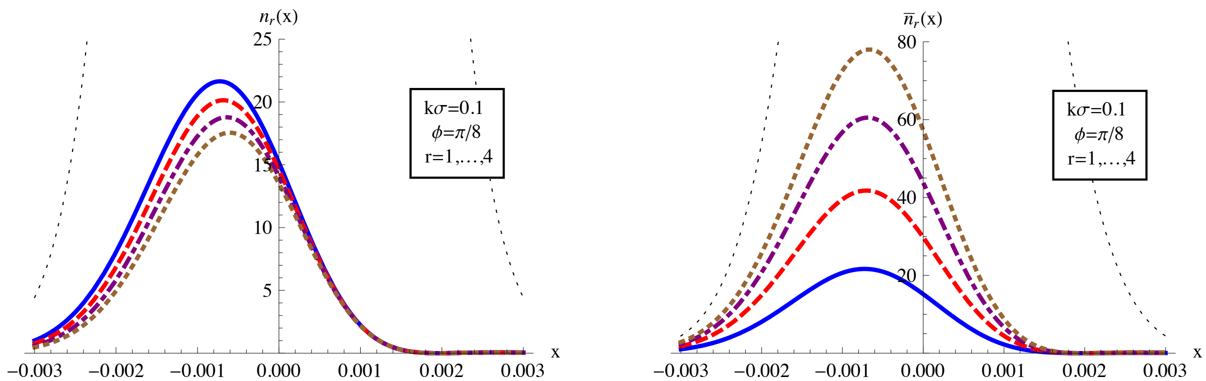


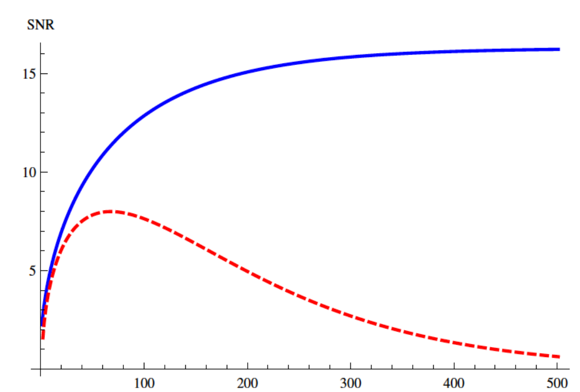
Fig. 4 The amplified signal comes from the anomalously large lateral shift, so this walk-off degrades the amplification properties of the setup with increasing r (r =1 [blue], r =2 [red], r =3 [purple], r =4 [yellow]). Each individual cycle dark-port profile is shown on the left, while the integrated dark-port profile (i.e., summing the output of all cycles $\leq r$) is shown on the right. In the limit of an infinite number of cycles, the original (unamplified) Gaussian is recovered, indicating there will actually be *no* tilt-dependent signal.

that one indeed continues to accumulate a deflection even in the limit of a large number of cycles. Figure 6 shows our preliminary calculation of the advantage of using such a technique.

b. Use quantum Zeno stabilization, in which the beam is projected back onto a Gaussian spatial profile each round, by placing a spatial filter between the PBS and mirror (see Fig. 1). Any light passing through the filter would be essentially projected back into its initial state on each pass†. With such stabilization the dark port would obtain identical post-selected beam spatial profiles with each new traversal; hence, the accumulated intensity at the detector would exactly follow the aforementioned heuristic power scaling of the SNR, with the same amplified displacement for each pass.

Assuming these effects can be minimized, putting in practical estimates for typical system parameters, we estimate an order of magnitude improvement of the multi-pass recycling scheme SNR over the single-pass SNR. Realizing such improvements is one main goal of our current project.

Fig. 6 A sample SNR plot shows the effect of mode reflection to maintain the advantage of multiple recycling. The SNR with reflection is represented by the blue solid curve, while the red dashed curve simulates the original experiment with no spatial mode reflection at the bright port.



† Our preliminary theoretical calculations indicate that for a weak-measurement post-selection probability of 0.5% per cycle, the loss due to Zeno projection over 100 cycles will be << 10^{-5}, i.e., negligible.

References

[1] D. J. Starling, P. B. Dixon, A. N. Jordan, and J. C. Howell, "Optimizing the signal-to-noise ratio of a beam-deflection measurement with interferometric weak values", Phys. Rev. A **80**, 041803 (2009).
[2] O. Hosten and P. G. Kwiat, "Observation of the Spin Hall Effect of Light via Weak Measurements", Science **319**, 787 (2008).
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[4] P. B. Dixon, D. J. Starling, A. N. Jordan, and J. C. Howell, "Ultrasensitive Beam Deflection Measurement via Interferometric Weak Value Amplification", Phys. Rev. Lett. **102**, 173601 (2009).
[5] J. Dressel, K. Lyons, A.N. Jordan, T.M.Graham, and P.G. Kwiat, "Strengthening weak -value amplification with recycled photons", Phys. Rev. A **88**, 023821 (2013).
[6] S. M. Barnett, C. Fabre, and A. Maitre, "Ultimate quantum limits for resolution of beam displacements", Eur. Phys. J. D **22**, 513 (2003).